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# Improved modelling of lifestyle changes in Integrated Assessment Models: Cross-disciplinary insights from methodologies and theories

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ABSTRACT

Recent studies show that lifestyle changes can provide an essential contribution to achieving the Paris climate targets. While some efforts have been made to incorporate lifestyle changes into model-based scenarios, the attempts are currently very stylised and included exogenously. This paper discusses current efforts to represent lifestyle change in models, and analyses potential insights from relevant scientific disciplines to improve the representation of lifestyle changes in models – including modelling specific behaviour changes, identifying cross-cutting lifestyle solutions, representing the intentions behind the changes and quantifying their impacts. As such, this research attempts to bridge the gap between qualitative and quantitative theories and methodologies. Based on the results of this literature analysis, we recommend defining lifestyle changes more harmoniously, exploring an expanded range of approaches, domains and transformative solutions, adopting a whole-systems approach, and addressing the trade-offs between the use of exogenous inputs and endogenous modelling.

## 1. Introduction

Scenario analyses show that greenhouse gas emissions need to be reduced drastically to limit the rise to well below 2 °C in global mean temperature as per the Paris Climate Agreement [1]. Integrated Assessment Models (IAMs) are used to explore strategies for climate change mitigation to inform decision-makers. The options considered in these models generally consist of energy efficiency improvements, changes in energy supply (i.e. increased use of renewable energy, nuclear power and carbon-capture-and-storage), reduction of non-$CO_2$ emissions, and changes in land use. Various studies have attempted to improve the demand-side representation in IAMs in the use of efficient technologies. However, there is significantly less focus on lifestyle change modelling due to the topic's complexity and consumer heterogeneity [2–4]. Although assessment reports and other scientific papers highlight the potential of lifestyle change (e.g. related to transport, diet, appliance use, and thermal comfort) to reduce carbon emissions [5–7], they are modelled via relatively stylised assumptions in scenarios [3,4,6,8–12]. Furthermore, the comprehension of what sustainable lifestyles entail, and the motivations behind them, is limited within IAMs.

For policymakers, choosing between a variety of different policy options requires information about the probable outcomes of these decisions, especially in complex systems and with far-reaching implications. As is demonstrated in the fifth IPCC Assessment Report (with influence on the Paris Climate Agreement [5]), IAMs have a considerable impact in mitigation analyses by showing suitable options to achieve stringent climate targets [13]. However, it also implies that the focus on, or exclusion of, specific options in IAMs, can have consequences for the information on mitigation action provided to policymakers.

These two observations highlight the need for a better understanding of behaviour change and lifestyle-focused solutions within global, model-based scenarios. Other disciplines have paid considerable attention to consumer behaviour. The field of Sustainable Lifestyles, for

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instance, focuses on the more qualitative perspectives on this topic and has great potential in strengthening the understanding of the drivers behind behaviours. Within this context, this paper aims to enhance the knowledge of how to improve the representation of lifestyle changes in IAMs, by providing a multidisciplinary, comprehensive and comparative overview of research on lifestyle changes in different disciplines and identifying promising approaches.

Due to the differences in perspectives on lifestyle changes across disciplines, common misunderstandings can readily occur. Therefore, essential concepts must be defined carefully. As such, in Section 2, various distinctions, interpretations and definitions of lifestyle changes are elaborated to highlight differences and similarities among different fields and disciplines. Furthermore, this section explains the methodology of the systematic literature search. Section 3 emphasises the need for incorporating lifestyle change options within IAMs while noting the different ways of integrating them. Section 4 provides an overview of the different types of lifestyle change, distinguishing between domains, disciplines, methodologies and focus, and presents the results of this overview. Furthermore, this research analyses the various methodologies that have been used to integrate or model sustainable lifestyles by drawing from the literature review, from both the intent- (i.e. motivation) and impact-orientation (i.e. outcomes). In Section 5, we made recommendations and conclusions based on the opportunity for synthesis of lifestyle changes into IAMs by highlighting promising approaches, pitfalls and interesting entry-points from this literature analysis.

## 2. Distinctions and methodology

A comprehension of the various perspectives on lifestyle change is required to review the literature adequately. Different interpretations of lifestyle change are hence first discussed, followed by an explanation of the methodology of the literature search method and the review assessment.

### 2.1. Important distinctions and concepts

For the aim of this research, a definition of lifestyle changes is needed that is relevant for implementation in IAMs. IAMs are used to make assessments by comparing different options in terms of prices/costs and the service provided. Changes in costs can thus lead to substitution among available options. For instance, for any given electricity demand, the model could compare the costs of providing this electricity from wind power, a coal-based power plant or an alternative coal-based power plant with carbon capture and storage. Based on their relative costs and the required satisfaction of policy targets, the models determine the market shares for each of the above technologies, allocating larger market shares to low-cost options. A similar approach can be used to prioritise efficiency investments. In such cases, IAMs can be used to compare options that represent high- and low-$CO_2$ technologies, as long as the service they provide can also be easily compared [8]. Although IAMs often aggregate the representation of demand more than supply. Nearly all models include efficiency improvement, which assumes the adoption of an efficient technology/products (e.g. fuel-efficient vehicles), and technology-substitution, the use of different inputs (e.g. less $CO_2$-intensive fuel usage).

Measures that would lead to radically different levels of service output are, however, more challenging to represent in a similar context – as it would require a statement of differences in service level in the same monetary terms (i.e. costs). For instance, analysing decisions to travel less is more difficult on a like-to-like basis compared to the previous examples. In the literature in general (even beyond modelling) there is often an underrepresentation of possible ways to reduce emissions with measures leading to other services (e.g. driving less or taking public transport instead of the car if this leads to longer travel times) [14].

Consistent with the discussion above, modellers make a clear distinction between efficiency, technological substitution and lifestyle change, which can be defined as follows [15]:

- efficiency represents the provision of the same output with a lower input requirement (for example using a more efficient car);
- technological substitution represents providing the same output – but using a different set of inputs (e.g. wind power versus a coal-fired power plant);
- lifestyle change replaces the output for a different (relatable) service (e.g. travel less).

It is vital to discuss the difference between these types of changes, how other disciplines treat these distinctions, and how they relate to different domains (discussed in Section 2.1.1). A second relevant distinction is that of motivation and outcomes. Models make a distinction between autonomous changes (included in factors that change over time) and specific choices based on costs. They typically represent the latter as a response to price-changes that denote a generic 'climate policy'. Therefore, while models represent policies as a cost increase of options that lead to climate change, this price increase could also represent other forms of climate policy such as regulation or information. However, in reality, many choices are made based on non-monetary factors that could also influence greenhouse gas emissions. For that reason, there is also a critical second dimension - that of intent- (or motivation) versus impact-oriented (or outcomes) perspectives of behaviour change (discussed in Section 2.1.2). A final aspect requiring clarification relates to the domains of lifestyle changes, i.e. regarding food consumption, household energy choices, transport and consumption of goods (discussed in Section 2.1.3). This paper focuses on the behavioural aspects of consumer end-use (i.e. consumer *behaviour* and *lifestyle changes*), and not on representatives of businesses or institutions.

#### 2.1.1. The role of avoid, shift and improve

By building on the distinction of *efficiency*, *technological substitution* and *lifestyle change* defined in Section 2.1, we compare them to related distinction in the literature (see Fig. 1). For instance, Samadi et al. [15] make a similar distinction between *efficiency*, *consistency* and *sufficiency*, respectively, and defined as follows: "efficiency is an option in which the input-output relation is improved…consistency aims at fundamental changes in production and consumption by substituting non-renewable resources with renewable resources…[and] sufficiency is linked to the level of demand for goods and services". This distinction also overlaps with the distinctions of the avoid-shift-improve (ASI) framework [16]: *improve* matches with *efficiency* and *technological substitution* (i.e. *consistency*), while *shift* and *avoid* corresponds to *lifestyle change* (i.e. *sufficiency)* (see Fig. 1). This multidisciplinary paper highlights similarities and differences between the terminology that is used across the different disciplines and emphasises potential overlapping theories. This approach allows for easier identification of which theories, from other disciplines, IAMs can utilise. Many models can distinguish between these different types of changes; in reality, this difference is not always clear-cut. For example, electric vehicle adoption could be considered a purely technological substitution (i.e. *improve*) if the consumer adopting it has short commutes and with sufficient infrastructure. However, in other contexts, with inadequate infrastructure, electric vehicle adoption *could* be considered a lifestyle change (i.e. shift) as the service provided is different, and therefore not directly comparable. For example, fossil fuel-based vehicles offer more service in terms of range than electric cars, making the latter less attractive for car owners [2].

Food-related lifestyle changes are difficult to categorise, as they have indirect emissions and less related to technology but also because it is heavily dependent on the type of food. For example, organic food might be an improvement for some environmental impacts (impacts associated with fertiliser use, pollution) but could also lead sometimes to increased impacts (land use and associated greenhouse gas emissions). Therefore, for categorisation, we assume that the lifestyle changes can be either

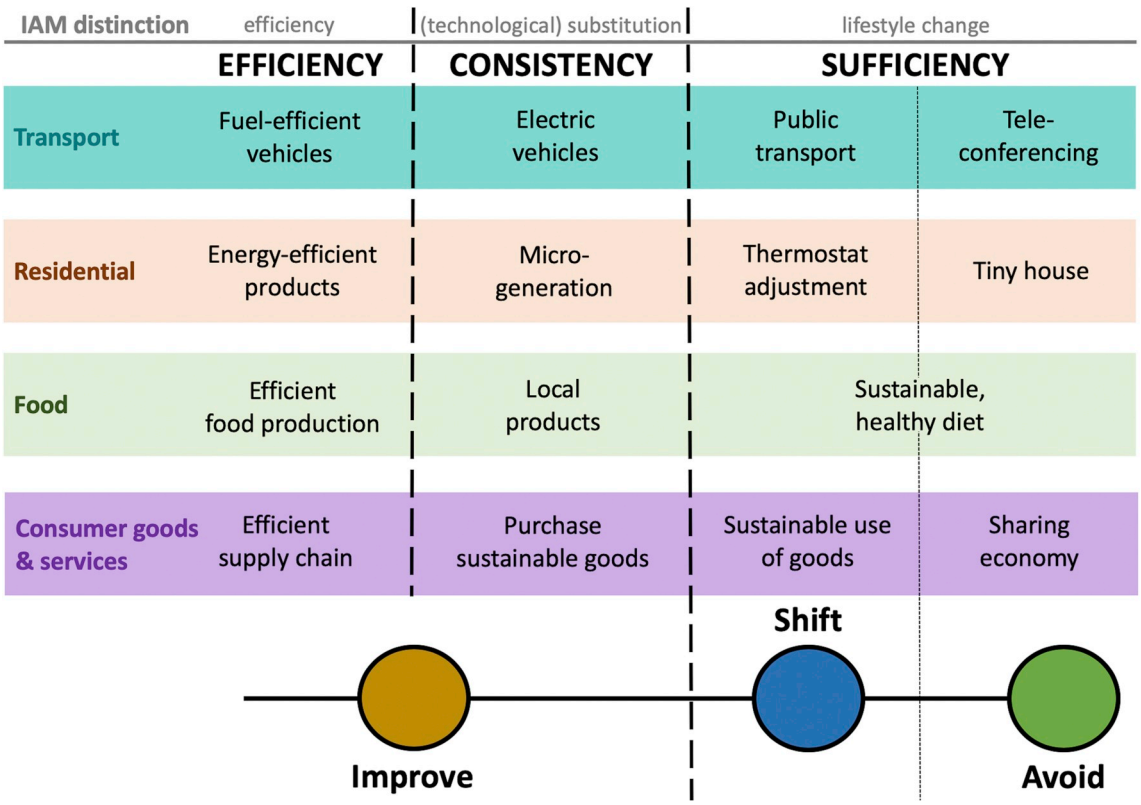


**Fig. 1.** Different types of behaviour changes are represented with examples in the domains relevant for IAMs (i.e. transport, residential, food and consumer goods and services) based on the distinctions between IAM distinction, 'efficiency', 'consistency' and 'sufficiency' by Samadi et al. [15] and the 'avoid-shift-improve' framework by Creutzig et al. [16].

positive or negative impact depending on the context (see Fig. 1). A sustainable and healthy diet could be both a *shift* towards alternative proteins and an *avoid* because it requires the consumption of fewer calories (and in some contexts more). Therefore, the context surrounding the lifestyle changes is vital in determining its ASI category, whether it has positive or negative impacts and consequently for identifying suitable interventions. For decreased complexity in ASI categorisation, this paper assumes contexts in which lifestyle changes lead to positive environmental impacts. In other words, *if* a lifestyle change *would* have a positive environmental impact, *where* would it be categorised? Context-dependencies may include regional differences, infrastructure, cultures, norms, values and domains. This ASI distinction hence becomes useful in determining the levels of the types of lifestyle change, especially for those represented in IAMs. Fig. 1 is adapted from the ASI framework [16], the efficiency, consistency and sufficiency definition [17] and categorised in line with the IAM terminology. The range of these different lifestyle changes in the various categories and domains is particularly relevant for IAMs and highlights where different actions or products lie within this range.

Based on these distinctions from the different terminologies, a definition suitable for the implementation of lifestyle changes in IAMs is:

Lifestyle changes are the changes that lead, or aim to lead, to the avoidance, shift and in some cases, improvement (depending on the context) in energy service demand, irrespective of their intent.

For this research, we will continue using the ASI distinction, as it offers more categories related to lifestyle changes, compared to the other distinctions (see Fig. 1). Even though we consider both *efficiency* and *technological substitution* within the *improve* category, it is essential to note that they do have different characteristics.

### 2.1.2. The role of intent and impact

A more effective analysis of the types of lifestyle changes requires an understanding of the motivations behind them, and the effects they have (see Fig. 3). The latter has been the predominant focus of IAMs so far, yet, a better understanding of the motivations is necessary to improve the representation of lifestyle changes in IAMs substantially. Gifford et al. [14] explain the differences between intent- and impact-oriented behaviours as follows: "Intent-oriented behaviour that focuses on the consumer's intention, and impact-oriented behaviour that focuses on the behaviour's environmental impact, do not always overlap." Some disciplines tend to focus on the motivation for change, such as 'sustainable lifestyles', 'psychology', 'behavioural economics', 'sociology', and 'philosophy'. These disciplines focus on the decision-making process of changes in behaviour (intent-oriented behaviours; see relevant quotes in the Supplementary Infromation). Other disciplines, such as 'industrial ecology' and 'energy modelling' (including IAMs), focus on the quantification of environmental impacts (impact-oriented behaviours). For example, consider flying from Amsterdam to New York for a vacation instead of taking a train to a closer destination. From an intent-oriented perspective, understanding the reasons, function and thought-processes for the journey constitutes the primary focus. From an impact-oriented perspective, however, the impacts and effects of that journey are of central interest. Both the intent- and impact-oriented behaviours depend heavily on the context or region in which lifestyle changes take place. This system perspective could be particularly useful for IAMs. If the models would adequately represent the intent-oriented behaviours, and quantify the impacts of these behaviours, they could quantify a change in behaviour based on both the motivation- and outcome potential. Therefore, it is vital to consider *both* these perspectives (to a certain degree) to get a full picture.

Furthermore, environmentally-friendly actions are often not motivated by environmental concerns; for example, vegans often eat plant-based foods for health rather than ecological reasons. Usually, only a weak association between pro-environmental behaviours and

environmental attitudes is observed [14]. In addition to differences in intent, there are also differences across disciplines in describing the intention of behaviour. For example, psychology focuses on personal psychological reasons while sociology would describe the cultural and social reasoning. The intent- and impact-oriented behaviours illustration in Fig. 3 highlights how these different perspectives construct a systems-perspective. Essentially, when a behavioural action occurs, there is motivation (i.e. intent-oriented behaviour focus) behind that action and an outcome following that action (impact-oriented behaviour focus). The distinction is one of the lenses through which the literature is analysed (see results in Section 2.3).

#### 2.1.3. Different domains of lifestyle change

IAMs treat energy and land use demand in detail. From a consumer behaviour perspective, consumption can be divided into four domains: 1) transport, 2) heating, cooling and appliance use in residential homes, 3) food and 4) the use of goods and services. Both the residential and transport domains are mostly related to "direct" emissions during the use phase. However, for food and consumer goods and services emissions are mostly generated in the production phase. Still, consumer behaviour can strongly influence demand for food, goods and services. For example, buying fewer goods by reusing, repairing or sharing, or purchasing sustainably-produced goods would be represented in the consumer goods and services domain [17–19]. As stated by Grubler et al. [4] "consumer goods are not an end-use service per se, but provide for cooking, lighting, hygiene, entertainment, communication and other useful services principally within the home".

There are also connections *between* the domains. For instance, leisure-related changes could influence all categories. Sustainable lifestyles literature and other empirical studies often identify leisure as a domain on its own. However, in the analytical context of models, if models define leisure as a separate domain, it would overlap with the four domains identified above. Furthermore, other changes *within* domains could also be cross-cutting. For example, washing clothing at lower temperatures to increase the lifetime of clothing (*consumer goods and services* domain) also leads to a lower residential electricity demand (residential domain). As the above examples make clear, the categorisation of domains for lifestyle changes is heavily dependent on the service defined for the action. The distinction between different domains is one of the lenses through which the literature is analysed (as is highlighted in Fig. 3 in Section 2.3 and results illustrated in Fig. 4 in Section 4.1).

### 2.2. Literature search

This paper conducted a literature review to improve the understanding of lifestyle change and sustainable behaviour from different perspectives. Furthermore, it illustrates where overlapping concepts and methodologies lie, and to assess to what extent IAMs can make use of information and apply useful theories from other fields and models. From these distinctions discussed in the previous section, we conducted a systematic literature search by refining the selection process to the articles relevant for this research. The literature search was carried out based on general search terms within article titles, abstracts and keywords, resulting in a broad and diverse selection of publications. We also included other relevant articles outside of the systematic search (see Fig. 2). We used the search terms and followed the selection criteria (see Supplementary Information) in selecting the relevant articles for analysis. Fig. 2 illustrates that there is a predominant focus in the literature on the 'food', 'residential', and 'transport' domains modelled commonly in IAMs, in addition to the 'consumer goods' domain highlighted in other disciplines or models [17]. Thirty-three articles focused predominantly on food and diet, sixty-two articles on transport, fifty-nine articles on the residential sector, and four articles have a significant focus on 'consumer goods'.

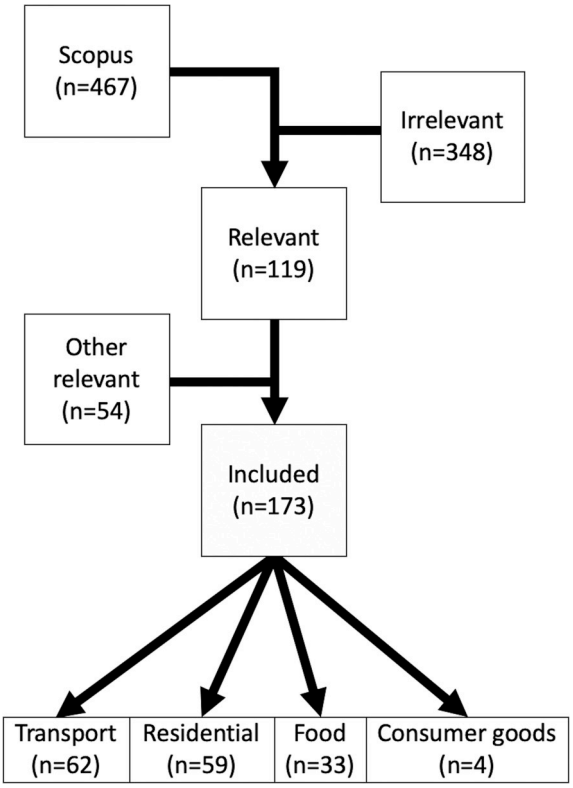


**Fig. 2.** Selection procedure and number of articles that focus on domains in the literature.

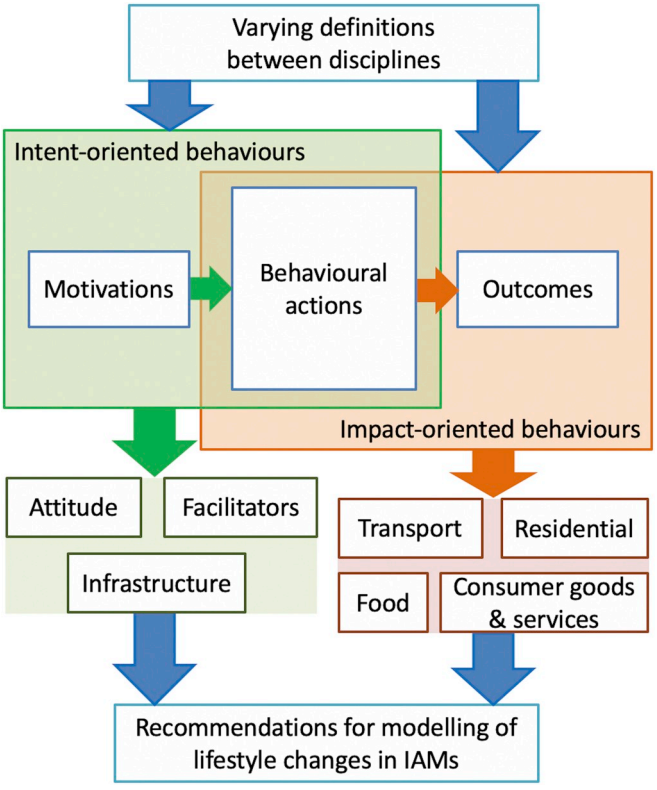


**Fig. 3.** Research approach illustrating how the various underlying definitions form the basis for the distinction between intent- and impact-oriented behaviours that frame the structure of the literature analysis, to formulate recommendations.

### 2.3. Approach

This research bases its approach (see Fig. 3) on the distinction between intent- and impact-oriented behaviours (described in Section 2.1.2) in order to capture both the motivations as well as the outcome of behaviours, and analyses these using the ASI distinction (described in Section 2.1.1) and different domains (described in Section 2.1.3). Looking at both aspects not only improves our understanding of how behaviours can be changed but also which behaviours should be changed. We first unpacked the impact-oriented behaviours and the disciplines that focus on these, such as Industrial Ecology and Energy Modelling (e.g. IAMs), but using a lens of intent-oriented behaviours. We did this by categorising them as 'improve, 'shift' or 'avoid'. After that, we analysed the disciplines focusing on intent-oriented behaviours, with the lens of modelling from the impact-oriented behaviour. We achieved this by highlighting relevant methodologies and theories for IAMs, and other models, within the categories attitude, facilitators and infrastructure influencing the motivation of behaviours. From this, we gained insights into the possible linkages between these different perspectives. More specifically, we formed concrete recommendations of how IAMs can learn from other disciplines (both qualitative and quantitative) to improve modelling or representation of behaviour.

## 3. IAMs and their coverage of lifestyle changes

As indicated before, IAMs have primarily focused on technology measures (i.e. improve), and only a few studies have integrated lifestyle change into their models. Mostly, the definition of this lifestyle change is a shift to actions that provide the same outcome (e.g. distance travelled), and less on the avoidance of activities, (e.g. reduced travel) [8]. Therefore, there is a noteworthy gap in the representation of lifestyle change within IAMs. To identify promising approaches to addressing this gap, modellers need clarification on the possibilities within IAMs. There are several possible ways of modelling lifestyle changes in IAMs, which are discussed in more detail below:

1) Incorporate changes in lifestyle into narratives, or storylines (e.g. similarly to the Shared-Socioeconomic Pathways), with exogenous representation in IAMs.
2) To a certain degree, lifestyle changes can be modelled endogenously with adjustments of parameters and assumptions within the IAMs.
3) Explicitly model lifestyle changes entirely within the IAMs (e.g. with a whole module focused on lifestyle changes that dynamically responds to other modules).

The use of narratives or storylines is a relatively simple way of improving the representation of lifestyle change in IAMs. This method is not new, but the storylines themselves could be improved significantly in terms of lifestyle changes. More specifically, IAMs could improve the storylines by drawing from qualitative research that specialises in understanding how consumers could change their behaviour over time. A notable example of how narratives have been used to create baseline scenarios is the use of the Shared-Socioeconomic Pathways (SSPs) framework [20]. This framework structures the uncertainties around lifestyles and other drivers into five narratives, based on the challenges to mitigation and adaptation. These narratives provide assumptions regarding lifestyles for developing scenarios by IAMs; however, they still only offer a relatively small range of possible trajectories. Recently, van Vuuren et al. [3] modelled lifestyle changes within a scenario with exogenous inputs, including "less meat-intensive diet (conforming to health recommendations), less $CO_2$-intensive transport modes (following the current modal split in Japan), less intensive use of heating and cooling (change of 1 °C in heating and cooling reference levels) and a reduction in the use of several domestic appliances", among other similar studies [8,10,21,22]. Likewise, van de Ven et al. [9] modelled behavioural options around food demand, mobility demand and housing demand in the EU specifically, also based on stylised assumptions. Furthermore, a recent study, by Grubler et al. [4], represented lifestyle changes within narratives, with a 'low energy demand (LED)' scenario. They illustrated how changes in types of energy service and quantity drive structural change in the supply sector. Also, they concluded that down-sizing the global energy system dramatically increases the feasibility of reaching 1.5 °C climate target without relying on negative emissions technologies. They represented lifestyle changes (e.g. how consumers could change the way they use technology) as exogenous inputs. Compared to other optimistic scenarios on world final energy demand, such as the Greenpeace [R]evolution scenario with around 315 EJ/year and SSP1 1.9 W/$m^2$ scenarios with about 425 EJ/year, the LED scenario is considerably more optimistic with around 245 EJ/year. These scenarios are still very stylised and lack qualitative insights on long-term changes and regional differences. Moreover, as information about lifestyle change is often exogenous input to the models, it does not react to changes happening within the models. Therefore, the information is very dependent on external assumptions. The scenarios do, however, illustrate that improving the degree of representation of lifestyle changes in IAMs can lead to promising future scenarios in terms of transformative reductions in GHG emissions.

The second option for better representation of lifestyle changes consists of adjusting parameters and assumptions within IAMs to allow a certain degree of endogenous modelling. This methodology also requires significant insights from qualitative disciplines. For example, qualitative research can help IAMs improve the representation of decision-making processes or heterogeneity of consumers and how they could change. Edelenbosch et al. [2] made an effort to do this by building on the work of McCollum et al. [22]. They explored a dynamic representation of adopter groups' [23] behaviour in both technological- and social learning that influences a technological transition to battery electric vehicles (BEVs). This study is limited to this particular case study of the transport sector. Furthermore, other studies, such as van de Ven et al. [9] and Li [24] have introduced heterogeneity among decision-making within energy modelling. There are significant limitations for the representation of types of lifestyle changes through this approach. For example, some changes are more difficult to quantify than others (e.g. technology-related lifestyle changes are more straightforward to capture in IAMs than those unrelated to technology). Therefore, there is an opportunity to explore more ways of modelling integrative depictions of lifestyle changes, by learning from qualitative studies allowing for a better representation of lifestyle changes in IAMs.

Thirdly, explicitly modelling lifestyle changes within IAMs is a more challenging approach to represent lifestyle changes. Dynamic modelling requires a detailed understanding of future behaviours and the motivations behind them, and potentially an entire module within the model dedicated to lifestyles to incorporate dynamic interactions with other modules. One example of how this type of approach was applied is the study by Edelenbosch et al. [2], which modelled changing behaviour endogenously within IAMs by including the dynamics of social learning. Furthermore, this approach could address how consumers respond differently to changes in 2020, compared to 2050 and even 2100. Longer time horizons come with a significant level of uncertainty and thus require substantial inputs from other disciplines to understand how behaviours will change over time and across regions. This approach would be very challenging to implement, as the model dynamically models based on economic and technological factors. Therefore, if models would include social factors dynamically, they would have to be (to a certain extent) translatable to the existing categories within the models. In addition to the difficulty, the approach would allow for a limited range of lifestyle changes representation. This research hopes to gain a better comprehension of how to apply this approach of modelling in IAMs with a higher range of lifestyle changes possible, by drawing on both qualitative and other quantitative disciplines.

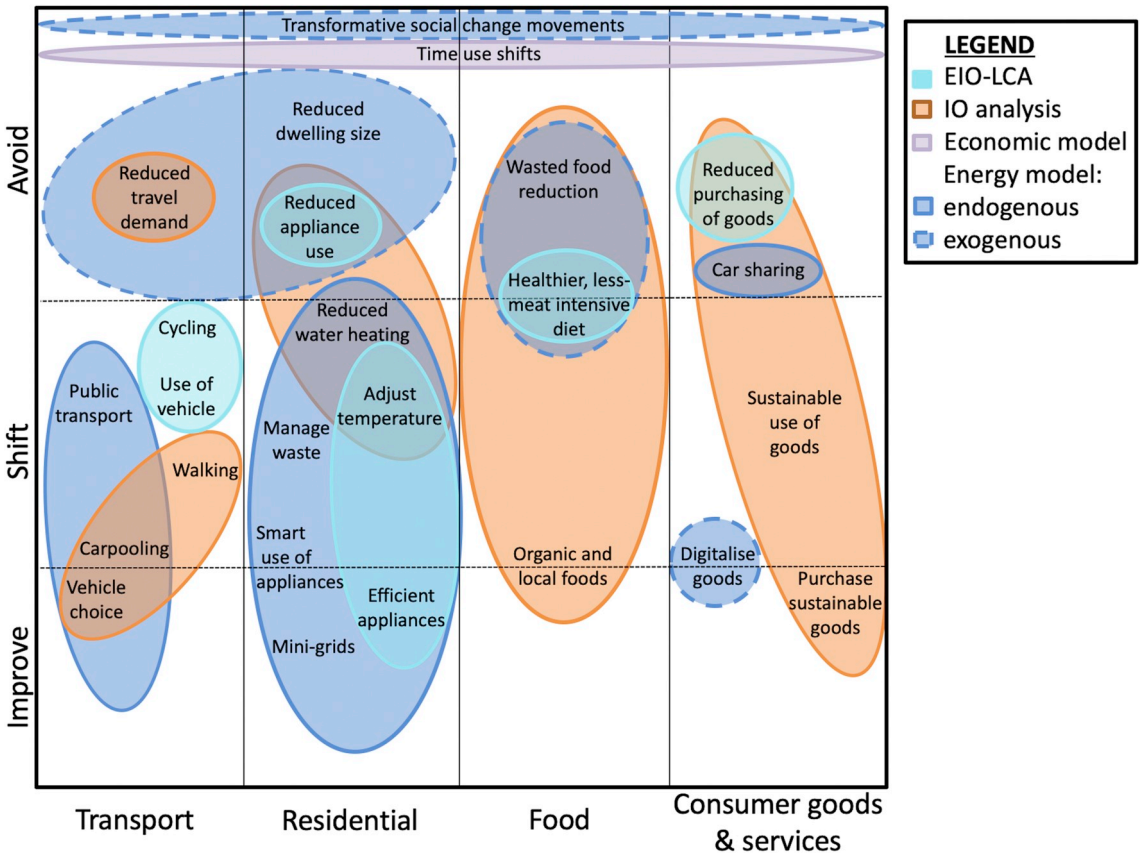


**Fig. 4.** Impact-oriented behaviours categorised in relevant domains used in various modelling techniques (x-axis) and as 'improve', 'shift' and 'avoid' (y-axis), namely EIO-LCA [27], IO analysis [25], economic model [19,31] and energy models [3,4,8–10,73].

## 4. Vital elements of lifestyle and behavioural changes across disciplines

This chapter explores both quantified impact-oriented behaviours, as well as intent-oriented behaviours by focusing on the drivers of motivations behind these behaviours.

### 4.1. Lifestyle changes across different domains

This section elaborates on the impacts of lifestyle changes, i.e. impact-oriented behaviours (see Section 2.1.2). An analysis of these impact-behaviours is discussed below through the lens of the ASI framework illustrated in Fig. 1 (see accompanying tables in the Supplementary Information for more details). The analysis (see Fig. 4) highlights the domains relevant for IAMs (as explained in Section 2.1.3) as well as the emphasis of modelling behaviour. The overview categorises lifestyle changes in 'avoid', 'shift' or 'improve' (see explanation in Section 2.1.1), in their respective domains (see description in Section 2.1.3), and what methodologies consider which lifestyle changes. It also emphasises the gaps and resulting opportunities in the quantification of lifestyle changes in IAMs – i.e. in consumer goods and services and food domains, endogenous modelling of 'avoid' category, and cross-domain factors such as time use shifts. The following sections analyse lifestyle changes in their respective domains to highlight the focus in the literature and gaps across domains (see Section 2.1.3 on the role of domains).

#### 4.1.1. Transport

The *transport* domain has been modelled relatively often with regards to lifestyle changes (see Fig. 4). Several of the modelled "lifestyle changes" fall outside our definition of a lifestyle change (i.e. *avoid* or *shift*), and constitute a technology change (i.e. improve). In transport, for example, 'choice of vehicles' is an *improve* and not a *shift* or *avoid* lifestyle change, as it is a switch to the same product with different inputs or higher efficiency. As was discussed before in Section 2.1.1, this could change depending on the context. Most of the measures modelled are *shifts* towards less intensive transport modes, such as 'public transport', 'carpooling', 'cycling' or 'walking' to the same intended destination. Lifestyle changes in the 'use of vehicles' have been modelled as well and would technically be a *shift* in behaviour within the transport domain. It requires a conscious change in behaviour to shift to eco-driving and maintaining vehicles, but its impact would be quantified at *improve* (i.e. efficiency improvement). The Environmental Input Output-Lifecycle Assessment (EIO-LCA) model is used for analysing lifecycles of products, such as vehicles. Thus, the EIO-LCA model allows for analysing lifestyle changes in the use phase of vehicles (i.e. the manner of driving the car) that affects both the efficiency and the vehicle lifetime. Some of the lifestyle changes modelled in the transport domain are in general (i.e. depending on the context) more transformative than in other domains within the same ASI category. For example, there are notable differences in the *avoid* lifestyle changes, 'reduced travel demand' in transport and 'reduced appliance use' in residential homes (see Section 4.1.2). However, in the transport domain, there is less variety in the types of measures found in the *avoid* compared to the *shift* in the transport domain.

#### 4.1.2. Residential

The impact-oriented behaviours falling under the *residential* domain vary significantly, and range from heating and cooling, changes in household dimensions, to mini-grids (see Fig. 4). Most of these lifestyle changes fall somewhere between the *shift* and *avoid* categories since many measures focus on the reduction of energy use. For example, 'adjust temperature', 'reduced water heating', 'manage waste' and

'smart use of appliances' can be considered as *shifts* in lifestyle, as there is no change in function but rather a change in the means to the service. In contrast, 'reduced dwelling size' is categorised as *avoid*, as it is a more radical, one-off decision that reduces emissions in multiple ways over an extended period. 'Purchasing efficient appliances' is efficiency *improvement*, as it requires a decision on a product with the same function, but also in the same way as its alternative. The use of mini-grids is a lifestyle change challenging to categorise in the residential domain, as it can be seen as an *improve* technological substitution but also has *shift* characteristics. This complexity can be due to the relatively high level of investment needed for a mini-grid, the difficulty of implementing it (potentially with the entire community), and intermittency related to the output of the mini-grids. Therefore, these residential measures are more complex to classify within the ASI categorisation, compared to the more-straightforward transport measures.

#### 4.1.3. Food

The literature review shows that the *food* domain has a limited variation in the type of lifestyle change, probably since the focus is predominantly on diet change (see Fig. 4). Furthermore, the disparity between ASI categories is also limited. For example, 'reduced meat-product consumption' would be represented by a *shift* or *avoid* depending on whether the function is calorie intake or meat consumption, respectively. While reducing food waste is categorised as *avoid*, and organic, local foods categorised as *improve* (e.g. when bought in a supermarket), the assumptions and the context heavily influence this categorisation. For example, a 2010–2030 transition from one diet to another is assumed by Stehfest et al. [10], while others consider a static change [25]. Frenette et al. [26] assume beef is substituted by less-emission intensive poultry and pork and thus a *shift* lifestyle change. While in the study by Stehfest et al. [10], beef is assumed to be substituted by plant-proteins (i.e. a reduction in meat) potentially categorised as *avoid*. Therefore, the distinction between ASI categories is far less apparent in the food domain, compared to transport and residential.

#### 4.1.4. Consumer goods and services

Few studies within the IAM community have quantified changes in behaviour in the *consumer goods and services* domain (see Fig. 4). Other approaches, such as input-output analysis [25] and LCA [27], focus primarily on the supply chain of commodities. Consumer goods and services are far less explored than the previously-discussed domains, perhaps because lifestyle changes in consumer goods and services have an indirect effect on energy reduction. The indirect impact is at the production stage or the landfill stage of the lifecycle, or the emissions quantified within other domains. For example, washing at lower temperatures as modelled by Bjelle et al. [25] focuses on the maintenance of goods (i.e. 'sustainable use of goods') to increase its lifespan (categorised as a *shift*). However, the same action also influences the use of hot water within the residential domain. Furthermore, reduced consumption of goods (i.e. 'reduced purchasing of goods' categorised as *avoid*) is effected by 'reduced dwelling size' (see the residential domain in Section 4.1.4 and Fig. 4). This dynamic interaction can be explained, as a smaller dwelling space reduces the need or possibility for goods to fill that space. Also, useful services, as modelled by Grubler et al. [4], highlights the value of a shared mobility lifestyle (i.e. 'car sharing'), which could lead to more public transport use and less car ownership (i.e. categorised as an *avoid*). Additionally, the 'digitalise goods' categorised as *improve* could have implications on the number of goods owned and also the efficiency of using those goods. Another *improve* change would be the 'purchase of sustainable goods', with lower emissions in the supply chain but also with extended lifespan. The categorisation of a lifestyle change in a particular domain, is, therefore, significantly dependent on the service defined or the motivation of the action. For example, heating a house or having a spacious house both have a similar measure of output (the motivation, or intent, is discussed in Section 4.2). Therefore, we can establish that the impacts of one specific lifestyle change can be quantified in several domains. These interactions make it even more evident why a broader range beyond domains is beneficial.

#### 4.1.5. Cross-domain lifestyle changes

This section discusses the categorisation of modelled lifestyle changes that do not fall in any of the domains discussed above (see Fig. 4). These cross-cutting lifestyle changes often influence other domains indirectly. For example, 'transformative social change movements' modelled by Grubler et al. [4] would indirectly affect diet, transport, residential and consumer goods and services domains. Including such transformative social change movements in models could potentially have substantial consequences for the feasibility of achieving ambitious climate targets. 'Time use shifts' is another promising entry point for exploring lifestyle changes. For example, the time spent engaging in different daily activities, as this might influence domains like transport and food. For example, working time reduction could result in less vehicular transport and healthier diets, while it will probably increase residential heating and cooling demand. There is a significant focus in the literature to emphasise aspects such as minimalism, slower lifestyles, or healthier work-life balances, which have positive outcomes on climate change mitigation. Some of the articles in this review have explored the concepts of slower lifestyles. For example, GLAMURS [19] modelled energy use and time use patterns at the macroeconomic level using the Macro-economic Sustainable Time Use (MaSTU) model, allowing for the analysis of both policies and consumer initiatives impacts directed to sustainable lifestyles. Furthermore, time affluence and time use are essential entry points for sustainability. These aspects are closely related to income and footprints, since there is a societal polarisation between people who have insufficient resources or time and those who do, whether they want it (e.g. more free time) or not (e.g. unemployment) [28]. Time use cannot be categorised in any specific domain, as it would have indirect consequences for multiple domains. It is reasonable to categorise these changes as *shifts* between domains but *avoid* within domains. For example, working a day less could result in lower energy demand in transport, but a shift in demand towards residential energy. While it can be interesting to understand the dynamics of the indirect effects of lifestyle changes on various domains, within the review, only a limited number of studies highlight this domain. These are often unmeasurable lifestyle changes in terms of costs or monetary factors, but possibly measurable in patterns of time-use of household members. These concepts are less commonly explored, especially within energy modelling, since they are more challenging to quantify. However, the cross-cutting characteristics can be useful when exploring related ideas, such as, changing the work-life balance and travel patterns. Therefore, they could be vital in understanding the effects of lifestyle changes on climate change mitigation.

### 4.2. Modelling determinants, influencing factors and direct drivers

Other categories modelled or analysed in studies from this review, did not fit the category of impact-oriented behaviours since they only focus on the intentions of consumers, i.e. intent-oriented behaviours. An overview of intentions (or determinants) is shown in Fig. 5 based on the systematic literature review conducted. The framework by Akenji and Chen [17] introduces the determinants *attitude*, *facilitators* and *infrastructure* on how to shape sustainable lifestyles, and these are adapted based on this literature review. These determinants help clarify what factors drive sustainable decision-making directly and influence them indirectly, in different disciplines (Fig. 5). This research also uses these determinants as a lens through which the various lifestyle changes and modelling techniques were analysed (see x-axis in Fig. 6). As observed in the literature from the review, these are often qualitatively modelled through narratives and storylines [29] or quantitatively with heterogeneous consumer groups [9,30,31] and different demographics [19,32]. These intent-oriented factors are more novel ways of modelling behaviour in IAMs and are useful in understanding both the intentions and,

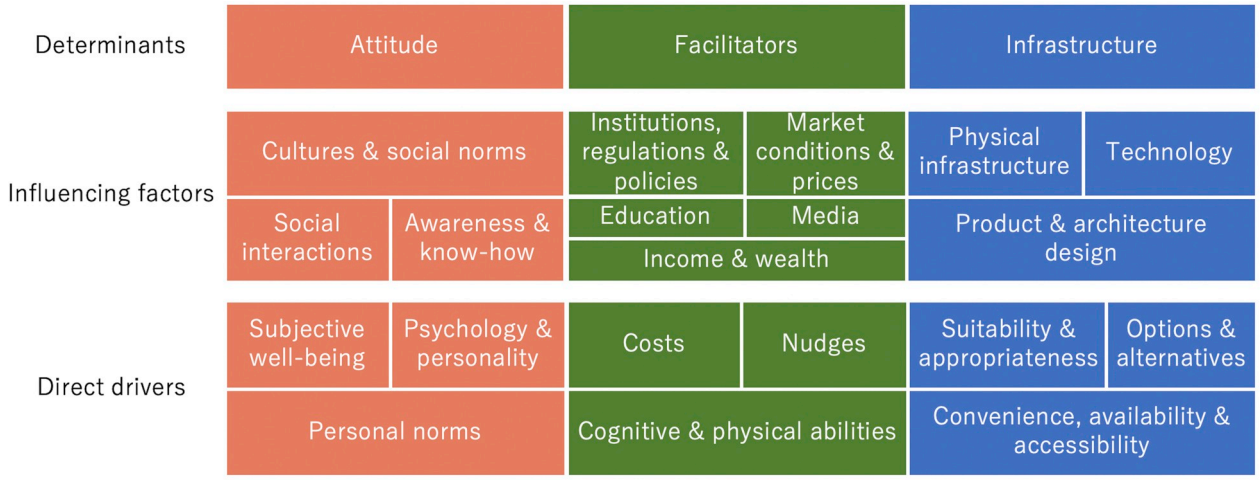


**Fig. 5.** Theoretical framework of lifestyles [17] adapted for integrating lifestyle changes in IAMs, based on the determinants 'attitude', 'facilitators' and 'infrastructure' which form one of the lenses for analysis of lifestyle changes.

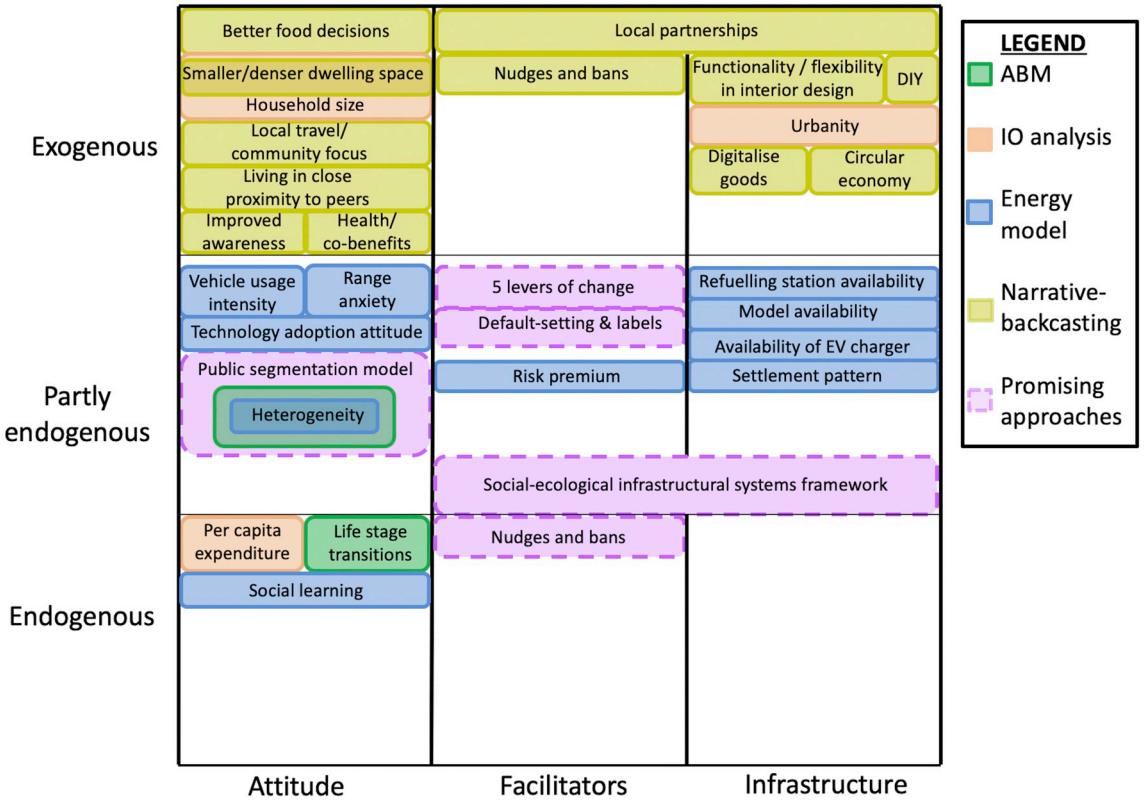


**Fig. 6.** Results of intent-oriented behaviours as categorised in determinants 'attitude', 'facilitators' or 'infrastructure' (x-axis), that were modelled/incorporated or showed promise to be included into IAMs, as 'exogenous', 'partly endogenous' or 'endogenous' (y-axis). These models include agent-based models (ABM) [19,24,31], input-output (IO) analysis [32], energy models [2,9,22,74], narrative-backcasting [29] scenarios and promising approaches [32,45,66,67,72,73].

consequently, the underlying causes of the impacts of behaviours. To expand the range of modelled impact- and intent-oriented behaviour factors, a more qualitative approach can help identify promising methodologies. These factors and the intent-oriented behaviours, already quantified, or incorporated into scenarios (see Fig. 6 and details in the Supplementary Information), will be discussed in the following sections and linked with the determinants (see Fig. 5). A modelling perspective has been used to summarise the literature review, by highlighting already modelled concepts and promising approaches, but also distinguishing the possibility to model them exogenously, partly endogenously or endogenously in IAMs (see y-axis in Fig. 6).

#### 4.2.1. *Attitude*

This section deals with the determinant *Attitude* and discusses the relevant factors (see red boxes in Fig. 5) with regards to the intent-oriented elements of behaviours (that could be) modelled (see Fig. 6). There is considerable recognition in the literature of the existence of a value-action gap, a situation where individuals identify with pro-environmental value but do not act accordingly [33]. The Theory of Planned Behaviour from the field of psychology, specifically the

Perceived Behavioural Control, similarly highlights the gap between intention and behaviour [34], focusing on the perceived difficulty or ease of acting on intentions. To better understand the size of this gap, self-efficacy – the assessment of how well an individual can execute actions to deal with potential circumstances – can help reliably predict behaviour [35]. This section deals with the factors affecting the attitude drivers and influencing factors of lifestyle changes (see Fig. 5). *Personal values, norms and beliefs* (see Fig. 5) affect our environmental identity, which in turn affect our awareness of consequences. This *awareness* (see Fig. 5) shapes our norms and the acceptability in both supply-side technologies and demand-side measures (i.e. behaviour), as illustrated by the Value-Belief-Norm model [36]. Awareness has been highlighted significantly in the literature review as a critical influencing factor and incorporated into scenarios [29] (see Fig. 6). A distinction can be made between 'compliance' (presenting pro-environmental behaviour when under scrutiny) and 'conversion' (self-sustaining the pro-environmental behaviour) if the goal is to generate sustained change [37]. Some authors theorise that reflection, deliberation and elaboration, can contribute to achieving and sustaining change in behaviour [38]. For example, the 'elaboration likelihood model' [39] suggests that sustained behaviour change relies on individuals consciously engaging with the subject matter and elaborating on it. However, there is ample evidence from the literature that higher awareness or belief alone is not sufficient to induce change, let alone sustain such change. Such is the basis of the common misconception built into public campaigns, that if consumers receive full-information and know-how, behaviours will change [40]. Among several examples, there are high correlations found between the intention to reduce meat consumption and make thermostat adjustments to less environmentally harmful levels, and little evidence of it happening [41].

Some authors have argued the need to look beyond the individual, and focus on collective action or broader *social norms* [37] (see Fig. 5) to overcome the climate value-action gap and achieve sustained change [42,43]. "Creating sustainable lifestyles requires a change in social norms…it means rethinking of ways of living…it's about transforming societies to better meet people's needs in balance with the natural environment" [17]. In this case, mechanisms such as social imitation and collective efficacy might be more predictive of a behaviour related to a collective outcome [44]. Collective or social interaction (see Fig. 5) has, to a certain extent, been modelled through social discounting [24], contrasting with individual discounting and endogenously modelled social learning [2] (see Fig. 6). This social learning can be a promising methodology to incorporate into IAMs to account for differences in social change and individual action. For proper representation of lifestyle changes in IAMs, modellers should account for these social norms influence over behaviour.

It is also essential to recognise individuality (e.g. *personal norms* and identities in society) and therefore capture the heterogeneity of citizens in IAMs, for different types of behaviours (see Fig. 5). Efforts have been made to incorporate this heterogeneity in energy modelling, to expand the types of consumers beyond the usually-modelled rational actors and free-market economists with cost-optimal decision-making (see *heterogeneity* category in Fig. 6). Diversity in types of profiles include 'scientifically-informed', 'environmentalists' [31], 'heterogeneous decisions with social discounting', 'heterogeneous decisions with individual discounting' [24], 'convenient', 'conscious' and 'enthusiastic' [9], and different adopter groups based on diffusion of innovations theory by Rogers [23], 'early adopters', 'early majority', 'late majority' and 'laggards' [22]. These methodologies can be expanded to include different consumer segmentation, which further grasp differences in consumer behaviours. An example of this is the evidence-based *public segmentation model* [45] (see Fig. 6), which aims to offer insights on how to stimulate various options for sustainable living for different segments. Studies that have implemented the segmentation models find inconsistencies between segments dependent on the sector (i.e. between activities, products and services), and therefore this approach would need to be tailored differently based on lifestyle changes in different domains.

*Well-being* (see Fig. 5) in the literature is usually associated with indicators that are alternatives to the Gross Domestic Product and aim to better portray social wellbeing, including new definitions of wealth, and new indices for the quality of life (e.g. Happiness Index). Putting well-being central on how to progress would thus necessitate that development of infrastructure, public policy, business strategy and institutional principles and practices are prioritised based upon their contribution to well-being. Some researchers, therefore, argue that *"dynamic models (with long time horizons) would need to consider the issue of influence of the physical and social context on preference formation"* [46]. Thereby, they are highlighting the need for modification of individual preference structures in IAMs resulting from changes in cultural or social norms about what "good life" and well-being signifies [15]. Some studies highlight the focus on well-being as a 'compelling, pragmatic and positive vision' on how sustainable behaviour can be adopted without scare tactics or guilt framing and instead with a focus on aspirations and stakeholder values [47,48]. Most notably, co-benefits of sustainable behaviour, related explicitly to well-being rather than economic benefits, are a commonly explored concept throughout the literature. There are numerous psychological barriers to changing behaviour, despite the positive subjective well-being effect and welfare. When a particular behaviour type has significant co-benefits (e.g. own health, societal health or animal well-being), it increases the consumers' willingness to adopt this behaviour [9]. These co-benefits can be modelled implicitly in different consumer profiles (discussed in the following paragraph) and in scenarios where health becomes communal issues (e.g. *better food decisions* as illustrated in Fig. 6). Understanding these co-benefits is the first step into determining how to stimulate and anticipate change [9, 49]. This focus on co-benefits allows a different framing of behavioural changes, to a more positive and compelling alternative, rather than a sacrificial decision.

Even though there is a tendency for actors located in the same regions to participate in similar mitigation practices, social norms related to sustainable behaviour often vary considerably within and across regions. Researchers speculate this is most likely due to clusters of environmental, social norms within regions [33]. These clusters within the regions are difficult to represent in IAMs, as these models *do* distinguish between regions *but* aggregate at that level, while models would need to represent social norms clusters *within* regions. Some examples from this literature review of differences in regions modelled include settlement patterns [22] and urbanity [32] (see Fig. 6). Furthermore, models could better represent different consumption patterns for regions in IAMs and incorporate interventions to promote generational changes within these regions. These changes could require social movements supporting long-term changes in social norms [50] (discussed earlier in this Section). Several articles address these concerns, by emphasising the potential of engaging people based on their stages in life (e.g. teenager, student and parent) [18]. For example, during life stage transitions (modelled by GLAMURS [19] using an agent-based model), or by acknowledging different consumption patterns in different life stages (modelled by Ala-Mantila et al. [51] using input-output analysis), for understanding possible opportunities for social change (see Fig. 6). These are novel ways of identifying possible shifts in behaviours, which could be useful for modelling lifestyle changes in IAMs over the long-term with demographic data on different life stages.

#### 4.2.2. Facilitators

"*Facilitators* are a set of factors that contribute to the possibility for certain behavioural patterns or a lifestyle to actualise" [17] (see green boxes in Fig. 5). *Public policy, pricing, nudge* techniques can facilitate sustainable lifestyles; and *institutions*, *markets*, *education*, and *media* could influence these techniques. Facilitators are the more relevant determinants from a policy-perspective as they are critical indicators to assess how likely a sustainable lifestyle can be adopted, and which levers can be useful in facilitating lifestyle changes.

*Cost* (see Fig. 5) is often assumed to be a dominant motivator and driver for decision-making [19,28], and thus also of lifestyle changes. Macroeconomic variables such as *prices*, *income* and employment (see Fig. 5) are therefore likely indirectly affect consumer decisions [19]. Traditionally, behavioural choices have been modelled by economists by assuming a utility function maximisation that represents their preferences, under rational choice theory [52]. This utility function represents which are the preferred options over others [46]. It is thus commonly assumed that rational actors make up the society, which maximises their gains at the least cost [53]. Currently, economic behaviour is often explained through this rational choice approach, for example, in IAMs and other energy models. Consequently, disclosed preferences form the basis of utility-maximisation, often conveying reduced generalised costs, including time [46,54–56]. Within the literature, there is quite some focus on Willingness To Pay (WTP), which is a concept where a higher cost is accepted by an individual, relating to a cost-benefit analysis weighing up the costs and the benefits of a decision [57]. Concerning environmentally-friendly behaviour, an intention for pro-environmental behaviour could be considered WTP [34,58]; to translate an expression of intent into action by using the appropriate facilitator. Often used facilitators involve costs and mitigation strategies; examples include taxes, subsidies, and deposit-refunds [19,53,59–61]. Some argue that mechanisms to foster cooperation should be incorporated into policies to become more effective in mitigating climate change but also account for irrational responses and uncertainty that could potentially inhibit collective action [62]. We argue based on the literature review results that Common-Pool Resource (CPR) theory can address the traditionally lacking reflexivity and disorganisation of climate policy, as the design principle of CPR theory can allow for a more comprehensive analysis regarding the effectiveness of policies. For example, design principles can offer an improved analysis of carbon taxes when compared to existing policy analysis, through better monitoring of user behaviour [63].

Some disciplines and theories challenge the above-mentioned rational choice theory based on cost-optimal decision-making, such as behavioural economics, psychology and welfare theory. For example, behavioural economics emphasises the need to understand the bounds of rationality of economic agents. Under the assumption that actors do not necessarily behave rationally, people are susceptible to *nudges* (see both Fig. 5 and Fig. 5), a term introduced by Thaler and Sunstein [64], which could improve decisions about wealth, happiness and health as well as environmental health (see relevant quote in Table S2). Fundamentally, thoughtful architecture can influence choices, through nudges or by steering consumers in a sustainable direction. However, some argue that nudges alone could be ineffective and must be combined with other approaches and incentives to achieve desired outcomes [64]. This concept is particularly relevant for IAMs since policymakers have become interested in the concept of nudging. They have become more reluctant to approach lifestyle issues with financial or administrative instruments that are perceived to limit freedom of choice [65]. As discussed in the previous section on Attitude (see Section 4.2.1), freedom of choice also highlights the importance of social context, social norms and values. Some interesting nudging-related mitigation strategies are *default-setting and labels* [66] and the use of *five levers of change* developed by Unilever [67] to break or create new habits (see strategies in Fig. 6). Furthermore, the narrative-based backcasting analysis included policy-driven nudges and bans [29] (see Fig. 6), and therefore has the potential to be either covered in narratives or modelled within IAMs.

#### 4.2.3. Infrastructure

"*Infrastructure* refers to socio-ecological interfaces that support consumption activities" [17] (see blue boxes in Fig. 5). There is an emphasis on context-specific conditions in the literature, which highlights the need for specific *appropriate* and *suitable* mitigation measures (see Fig. 5) to avoid a one-size-fits-all approach [68]. These measures also relate to the consumer-segmented method and modelling heterogeneity (see Section 4.2.1 on Attitude). For example, local GHG emissions drivers can be relevant in specific contexts only. Global models, such as IAMs, are therefore not adapted to understand or model these local emissions drivers, due to the lack of heterogeneity to appreciate specific impacts. By improving infrastructure heterogeneity within the models, they can address these limitations (similar to the those shown in Fig. 6). Therefore, IAMs could include varied infrastructure between *and* within regions (i.e. rural or urban) based on context-related factors for the various domains. This infrastructure heterogeneity can represent both motivation barriers *and* infrastructural barriers.

Lock-in designs limit and direct the choices available to consumers. For example, mobility *infrastructure* (see Fig. 5) favours private vehicle use, thereby limiting other options for travel, such as cycling or public transport [17]. As phrased by UNEP [40] "it is challenging for consumers to express demand for a product that is not available. It is therefore essential that retailers include more sustainable options in their assortment, and make these options attractive and affordable". Therefore, having *options and alternatives* (see Fig. 5) is vital to ensure that products or services both meet consumers' needs and have minimum impact on the environment. The design of products and buildings, for example, influences the level of convenience and options provided to consumers; therefore, *product and architectural design* (see Fig. 5) is a crucial influencing infrastructural factor. Currently, product design often ensures that replacement is intrinsic within the products (e.g. disposable razors) [59], limiting options for long-term use, recyclability or reparability. Subtle changes in product and infrastructure design can modify consumer behaviour [67]. Therefore, to improve the representation of lifestyle change in IAMs, enablers and lock-in factors for unsustainable and sustainable aspects should also be well represented [28]. Narrative-based backcasting by Neuvonen et al. [29] accounts for these concepts, with functionality and flexibility in interior design, DIY products and circular economy. Furthermore, McCollum et al. [22] account for *model availability* of light-duty vehicles to determine the likelihood of adoption (see Fig. 6). Infrastructure for transportation *convenience, availability and accessibility* are particularly relevant considerations for motivating sustainable behaviour [69]. For example, a 'smaller city block' system through improved spatial urban planning, enables pedestrians to change direction quickly [70], a factor that promotes accessibility and convenience (see Fig. 5). Similar elements have been modelled by McCollum et al. [22] using an IAM that considers *refuelling station availability* and *availability of EV charger* a factor in the adoption of light-duty vehicles. Therefore, by including these factors, IAMs can improve (partly) endogenous modelling of lifestyle changes, as they offer the context in which behaviour change is possible, or not (see Fig. 6).

Sometimes the lack of large-scale *infrastructure* (see Fig. 5) can lead to more sustainable behaviour. For example, in terms of decentralised energy systems in rural environments, small-scale infrastructure improves access to energy sources while also doing it sustainably, with off-grid clean energy sources [71]. This bottom-up infrastructure provision is also relevant for stimulating collective action. For example, "sustainable neighbourhoods, communities and cities are emerging through co-creation and participation" that is enabled by public space, buildings and urban infrastructure [65]. There is a trend towards collective action in terms of sustainable living. For example, transition towns or eco-villages [65], in which they use energy from their own local renewable energy production, requires appropriate energy infrastructure, such as micro-grids. Thus, the inclusion of *local partnerships* (see Fig. 6) in narrative-backcasting [29] and *settlement patterns* modelled in an IAM [22] (see Fig. 6) could be relevant factors affecting community-based energy provision, for inclusion in (other) IAMs or domains. Moreover, a promising approach to capture both the infrastructure and facilitators of intent-oriented behaviours could be through the use of the Social-Ecological Infrastructural Systems (SEIS) framework. This framework can be used to model the voluntary changes among users, and the interactions with policy actors and infrastructure

designers/operators [72]. Due to these overlaps found in both SEIS and IAMs, the approach of modelling the interactions between actors and infrastructure could also be of use to the modelling of interactions of behavioural changes within IAMs (see Fig. 6).

Lastly, *technological* innovation can enable alternative behaviours (see Fig. 5). Behaviour theorists emphasise technology's impact on behaviour and innovation's role as the agent of change [38]. This behaviour could fill a specific niche requirement, but could also spread to replace dominant technologies (i.e. disruptive innovations). Thus, technological innovation goes beyond focusing on the adoption of technologies by assessing *how* they can stimulate sustainable behaviour so that it is *convenient* and *appropriate* for each consumer (see Fig. 5). Technological innovation has, to a certain extent, been considered in intent-oriented behaviours, through the *digitalisation of goods* in a narrative-based backcasting analysis [29] (see Fig. 6).

## 5. Conclusions and recommendations for better representing lifestyle change in IAMs

This research discusses how different perspectives on lifestyle changes could be used to adopt a more nuanced and rich approach and representation of lifestyles in IAMs. We conclude that a meaningful way forward is to focus on the differentiation between *avoid*, *shift* and *improve* (ASI framework) and combining both intent- and impact-oriented methodologies while also representing the context and drivers of lifestyle changes. Even though we conducted a systematic review, critical articles may have been overlooked, especially with the ambiguity around the search terms and the variation in terminology between disciplines. Furthermore, due to the broadness of this research and thus limited time to go into detail, the categorisation of lifestyle changes modelled could be improved. Most notably, only a few frameworks formed the lens through which we analysed the literature. However, other frameworks could have yielded different results and relevant outcomes. Based on these conclusions and limitations, the following are recommended actions for, in particular, the IAM community, but also others to undertake.

### 5.1. Harmonise lifestyle change definitions, especially within the IAM community

The ASI framework allows a better, more qualitative, understanding of the variation in change from an impact-oriented perspective, and modelling approaches should distinguish these different types of lifestyle changes. Furthermore, this paper highlights the importance of semantics and how easily terms like 'lifestyle changes', 'behaviour', 'consumption patterns' are used as synonyms, but their meaning can differ substantially between disciplines. To interpret these concepts and guide strategy and action effectively, harmonise these concepts is crucial.

### 5.2. Expand the range of novel modelling approaches

Adopting the ASI framework can be achieved by experimenting with novel approaches to modelling lifestyle changes. This framework has a high potential for modelling lifestyle change endogenously (e.g. by using concepts such as life stage transitions or per capita expenditure). Furthermore, when IAMs cannot model lifestyle changes endogenously, they can still be dynamically represented by coupling IAMs with other models that prove beneficial where IAMs are limited (e.g. agent-based models or input-output analyses). Also, a promising way forward is to expand and strengthen existing methodologies within IAMs that have already proven successful, such as modelling social learning and heterogeneity on the intent-oriented behaviours by drawing from qualitative studies.

### 5.3. Expand the range of lifestyle domains and include cross-domain entry points in IAMs

To cover a broader range of lifestyle changes, IAMs could model additional factors beyond individual domains. A possible starting point could be to focus on cross-domain entry points (e.g. by incorporating shifts in time use patterns, social change movements), which have indirect effects on the traditional sectors in IAMs (such as transport and residential).

### 5.4. Expand the range of transformative solutions modelled

A stronger focus towards transformative solutions (i.e. actions within the *avoid* category), rather than efficiency gains and incremental adjustments, could emphasise the potential of lifestyle changes for climate change mitigation.

### 5.5. Add essential nuanced details to depict lifestyle changes in IAMs

Essential nuanced details allow for more detailed modelling of lifestyle changes with a greater understanding of the intentions from qualitative studies. This approach could strengthen model-based scenarios and thus clarify and improve communication to policymakers. For example, modellers can extend their modelling of 'shifts to public transport' to reflect variations in the types of public transportation, the frequency and distance of trips, and the co-benefits (e.g. both environmental and health benefits) that increase the desirability of particular lifestyle changes. Often the concepts, discussed in this research, to improve lifestyle change representation in models challenge the rational choice theory (used within IAMs), so it is critical to adapt models to move beyond this rational choice assumption.

### 5.6. Consider the whole picture, both intent- and impact-perspectives

If IAMs represent both the intent- and impact-oriented perspectives of behaviours, they could address the following questions: 1) Why do people change their lifestyles? 2) How can we stimulate these changes in lifestyles? 3) Which lifestyle changes are worth changing (i.e. have a relatively high impact)? One perspective without considering the other can result in only communicating half the story. Therefore, this joint perspective would benefit modelling lifestyle changes *and* effective communication to policymakers. Depending on the research question, there can be a skewed focus to either intent or impact. Nevertheless, considering the other perspective is very beneficial to account for the cause-effect relationship. For example, adopting an impact-oriented perspective is anticipated when modelling the outcomes of lifestyle changes, but could be better represented by reflecting on the intent-oriented perspective through the use of storylines.

### 5.7. Strategically address trade-offs between exogenous inputs and endogenous modelling

As can be seen in Fig. 7, on a scale from *abstract exogenous inputs* to *fully endogenous modelling*, there are trade-offs in terms of both empirical representation and dynamic representation. Using exogenous inputs can cover more of the lifestyle system and lifestyle energy use from empirical studies, and it is easier to implement. Therefore, using exogenous input has a higher potential for empirical representation. However, this approach to representing lifestyle changes lacks a dynamic representation of the uptake of specific lifestyle changes. Examples of exogenous modelling include stylised assumptions and narratives or storylines, and can either be executed ad-hoc (e.g. assumed a less-meat intensive diet [8]) or informed (e.g. narrative-based backcasting analysis [29]). Adopting an endogenous modelling approach limits the coverage of the lifestyle change system, but allows a better representation of changes in specific lifestyle choices. For example, consumer segmentation (e.g.

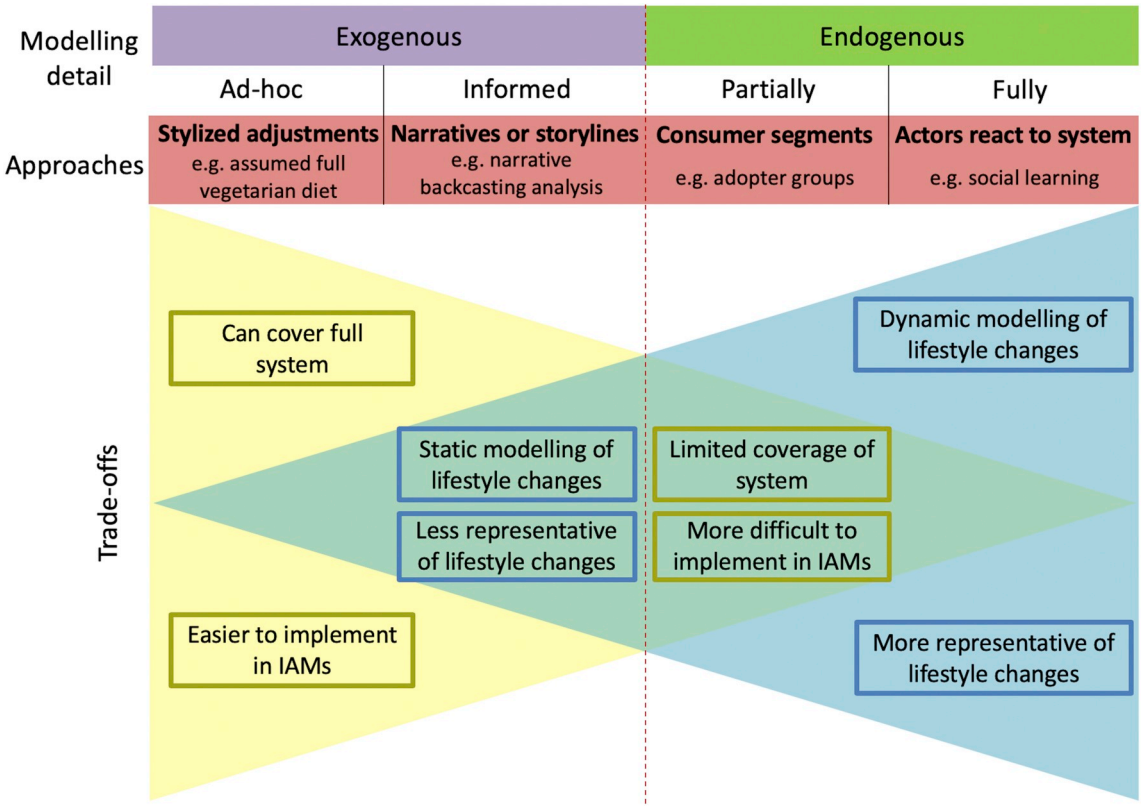


**Fig. 7.** Illustration of the trade-offs between exogenous and endogenous. From left to right shows a range of modelling opportunities from exogenous to endogenous. Under exogenous modelling detail, there are ad-hoc (e.g. with stylised adjustments) and informed (e.g. through narratives or storylines) options, while endogenous modelling detail, this can either be partially (e.g. through consumer groups) or fully exogenous (e.g. actors within the model reacting to other model sectors). The yellow triangle represents the trade-offs found when using exogenous inputs, and the blue triangle represents the trade-offs experienced when adopting an endogenous modelling approach.

adopter groups [22]), can be partially modelled within IAMs, while representing "consumers" reacting to specific lifestyle change options (e.g. through social learning [2]) could be fully endogenously modelled within IAMs. The chosen approach should depend on the research question. For example, for 'what-if' types of questions, static modelling with exogenous inputs would be more appropriate. If the main aim is improving our understanding of how a specific lifestyle change option evolves (e.g. increased use of public transit, lower temperature when washing clothing), a more dynamic approach would be more appropriate. Therefore, not one approach is stronger or weaker than the other: each approach has its strengths and weaknesses, and the chosen approach depends on the question put forward.

By following these recommendations, modellers can represent a more effective and fuller approach to lifestyle changes within IAMs. It is a necessary next step to support policymakers and decision-makers in acting to transform lifestyles towards sustainability and to reach our collective climate targets.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2019.100420.

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